Advanced Chemical In-Space Propulsion Critical Materials Research Requirements (Higher Priority than Solar Thermal)

Priority1 *Integrated Vehicle Health Management System*

Improvement in materials for future Space Transportation Systems is critical toward ensuring robust health and durability of spacecraft in extreme environments over extended periods of time. The criteria in this section can be viewed as materials input to integrated vehicle health management systems (IVHMS). Future requirements for system-level health will include the capacity of system components to resist wear and degradation from radiation, low temperature, micrometeoroid impact, high engine chamber temperatures due to the use of high performance propellants, high chamber pressures due to pump fed systems, etc.

Multi-layered coatings offer a means for achieving the materials properties required for advanced propulsion systems. Such coatings may consist of metals, ceramics, or polymers (Silicon or Carbon-based, for example). Methods for processing multi-layered materials could include atomic layer deposition (ALD), chemical vapor deposition (CVD), and chemical vapor infiltration (CVI), to name some examples. Several questions related to layer thickness, composition, control of defect content, coverage over complex geometries, compatibility at interfaces, phase behaviors, diffusivities, and response to space-based environmental exposure, among other properties, will be important areas of study.

Furthermore, there is a requirement for sensors that can actively control fuel mixture ratios in combustion engines using feedback loops. Wireless data transfer; lightweight cabling or fiber optics technology could be considered. Photonic systems have the advantage of being potentially impervious to radiation and electromagnetic pulse. Specific measurements include the concentration (fraction) of the various combustion products in the plume. Use lifetimes are up to 10-15 years in a hostile environment. Currently, flow rates and pressures are predetermined and there is no sensor and feedback control. The precise measurement of the combustion products and appropriate adjustments of flow rates of the fuel components could save up to 2% in fuel and oxidizer or propellant.

Priority 5 *Integrated Structure, Micrometeorid, Radiation, and Thermal Protection*

Advanced space transportation subsystems such as propellant tanks, propellant feed lines, heat shields, turbo-pumps, and enclosures will require advanced materials that can provide integral structural support, micrometeoroid protection, radiation and thermal protection. That is, a critical shortfall of conventional spacecraft subsystems is that these assemblies rely on structures to which protective features have been added after their development. There is therefore a critical need to incorporate these features in the materials design, analyses, and experimental testing phases *a priori*. Specifically, light-weight propellant management subsystems based on advanced materials and novel concepts will significantly reduce the inert mass of the in-space propulsion subsystem and lead to significant overall propulsion subsystem performance improvements; i.e., higher specific impulse. LOX and LH2 turbo pumps will require separate compatibility and low temperature thresholds relevant to their respective fluids. The study of materials including polymers, metals, and ceramics will be beneficial to the study of low-mass components for improvements in specific impulse. Opportunities for increased life and reliability of future turbo pumps (small-scale: less than 5K pounds of thrust) will further depend on materials effective in resisting thermal strain induced by engine operations.

Priority 4 *Lightweight Propellant Management Subsystem*

Current liquid propulsion systems for relatively low thrust spacecraft (1K – 5K lbs thrust) are limited to conventional pressure fed systems. Such systems limit the engine thrust chamber pressure to a few hundred psia; the resulting engine performance is thus limited, compared to higher thrust chamber pressure engines (1,000 psia). Pressure-fed versus turbo pump- fed versus reciprocating feed systems should be determined ultimately by an upper-stage architectural study. An integrated concept for high specific impulse should include these factors along with low mass materials considerations. Optimum propellant tank pressures, chamber operating pressures and temperatures depend on the propellant, and should likewise be optimized by upper-stage engineers. Current radiation cooled chamber materials are comprised of iridium coated rhenium chambers (up to 2200C). Research on refractory ceramic coatings onto the refractory metal chambers to extend the temperature range could be useful. New chamber temperatures are expected to reach 3473 – 4132C.

Priority 3 *Light Weight LOX Tank Critical Materials Research Requirements*

State-of-the-art lightweight LOX tanks experience ½% boil-off/year using multi-layer insulation (MLI). These boil-off rates are unsuitable for in-space propulsion over a 15-year lifetime. The development of LOX lightweight tanks with a mission life of 15 years, and an integrated structural/micrometeoroid/thermal protection subsystem with insulation that will result in nearly 0% boil-off is desirable. An experimental LOX tank has demonstrated zero boil-off for 3 months using a breadboard flight weight cryogenic cooler. Whereas budget limitations have suspended the latter development, a cryogenic cooler technology program could benefit from the study of many promising ultra lightweight materials such as aerogels and polyurethane.

Priority 2 *Light Weight LH_2 Tank Critical Materials Research Requirements*

A lightweight LH_2 tank with a mission life of 15 years with 0% boil-off and integrated structural/micrometeorid/thermal protection subsystem is required. LH_2 has continuous boil-off (2% per year) using multi-layer insulation (MLI), which makes LH_2 unsuitable for long-life in-space propulsion. The development of a flight-weight cryogenic cooler, which may provide zero LH_2 boil-off, is imperative for replacing high-mass Dewar technology. A cryogenic cooler technology program could benefit from the study of many promising ultra lightweight materials such as aerogels and polyurethane. A breakthrough in developing efficient lightweight insulation materials could result in LH_2 becoming competitive as an In-Space Propulsion propellant.

Priority 6 *Zero Outgassing Pressurant Critical Materials Research Requirement*

It is advantageous to remove inert gas tank liners (weight, system complexity, fabrication savings) and maintain purity of the contained inert gas (GN2, He, autogenous GO2, autogenous GH2, Xe, Kr) at high pressure. The issue is that the tank must be inert to the gasses, and sufficiently low in outgassing so as to ensure long-term purity of the gasses held within. Inert gas tanks currently use metal liners that can withstand He and GN2 gas pressures up to 10,000 psia. Low outgassing, lightweight structural materials have been investigated. Graphite-epoxy structural composites with radiation shielding, integrated electrochromic devices, and kapton encapsulated electronic circuitry have been reported (1999: "Light-weight structural materials with integral radiation shielding, thermal control, and electronics; Society for the Advancement of Material and Process Engineering (SAMPE)). Each high-pressure gas will be a separate technology task.

Priority Rationale

The rationale for the In-Space Advanced Chemical Propulsion Research Materials priority is:

1 IVHMS is the most important system for reusable, highly reliable, easily maintained, easily operated, and low recertification and turn around time. IT IS AN ENABLING TECHNOLOGY!

2 & 3 Light Weight LH_2 and LOX Tanks with zero boil-off will enable high performance (high I_{sp}[specific impulse]) LOX-LH_2 In-Space propulsion systems. Then maybe DOD will consider this propellant combination and get rid of the highly toxic and environmentally unfriendly Earth storable propellants.

4 Lightweight Propellant Management Subsystem will provide a high thrust chamber pressure for non-turbo pump fed systems.

5 Integrated Structure, Micrometeoroid, Radiation, and Thermal integration is more a cultural change among the engineering disciplines rather than a technology breakthrough. Nevertheless

this is an overdue discipline. Integration will provide an increased spacecraft mass fraction which results in an increase in spacecraft gross payload.

6 Zero Outgassing Pressurant Materials Research Requirements

The rationale for Solar Thermal Critical Materials Research is:

The canopy priorities (#4 and #5) are not high if an alternative means of rigidizing the primary inflatable reflector is found; the search for solutions to such an approach makes the Windowed Solar Thermal Engine materials requirements a high priority.

Solar Thermal Critical Materials Research Requirements (lower priority than Adv. Chem.)

Priority 1 *Solar Thermal In-Space Propulsion Research Materials*

One emerging area of study is operation of solar thermal engines as high temperature heat exchangers. This propulsion method will require concentration of solar radiation for the purpose of heating a monopropellant without combustion. Current state of the art is a pure rhenium engine in test (2800C). Technology challenges for the engine itself include the development of higher temperature heat absorbers from solar radiation (need temperature to reach ~ 3200C) and which are compatible with a hot hydrogen environment; development of materials with better creep-rupture properties than rhenium; development of leak-tight materials with higher melting point than rhenium; maximization of heat transfer between the heated surface and propellant.

Priority 2 *Windowed Solar Thermal Engines*

Windows for solar thermal engines is a high priority in solar thermal technology, therefore transparent materials that can withstand projected high engine temperatures (1500-3500K) with very low losses are desirable. Such a window material would enable direct absorption of solar energy by a non-equilibrium plasma or "seeded" hydrogen gas, thereby maximizing the gas temperature and minimizing heat losses. Windows could further provide a means for observing plasma properties in regions of interest. Windows in the solar radiation pathway from the primary reflectors into the plasma core would have a materials requirement approaching 100% transmission. Used as a refractive optic, the material would enhance collection efficiency as a secondary concentrator. The current state-of-the-art is quartz, which, with anti-reflective coatings to maximize transmission, can withstand 500-1500K.

Priority 3 *Solar Concentrator*

A critical requirement is to develop an optical quality deployable membrane primary concentrator (diameter = 10m; optimized packaging required to minimize volume during transit) designed for two years of use that will maintain 95% reflectivity at end-of-life; with smooth and reliable deployment after reaching its destination. Solar concentrators (polyimides: CP1 and CP2) have been demonstrated and ground tested (4x6m). Potential materials of study may include: Thin film dielectric mirrors (multi-layered, reflective materials) capable of 99% reflectivity are made with extruded sheets of many alternating polymer layers. Metal dopants (e..g., Ag or Pd complexed with 1,1,1-trifluoro-2,4-pentadionate (TFA)) in polyimide matrix yields films having > 99% reflectivity. Current materials of potential value have not been scaled to required size or demonstrated in the relevant combined environments for the full mission life. Processing of other possible candidates, such as dielectric mirrors, metallized polymers, etc., must be established and also demonstrated in the relevant combined environments for the full 15-year mission life. If a method for rigidizing the reflector without a canopy is found, then the solar transmissive canopy (priority 4) may not be as essential.

The secondary concentrator is part of the solar thermal engine. The secondary must be able to capture the large primary concentrator focal point and redirect the solar radiation inside the heat exchanger absorber cavity. The secondary must be either highly reflective (currently made of polished moly foil) or refractive (currently made of zirconium oxide crystal and sapphire materials) to minimize absorption losses. The secondary must withstand high temperatures being close to the engine absorber cavity.

Priority 4 *Solar Transmissive Canopy*

The solar transmissive canopy works in conjunction with the solar concentrator, enabling inflation and rigidizing of the primary inflatable reflector. The canopy is a mirror image of the reflector, but should approach 100% transmissivity. The reflector membrane and canopy are joined to form a lenticular structure. The space between these two lens-like structures is inflated to a particular pressure, which imposes the precisely required parabolic shapes for reflectance/transmission/focus, and thermal profile to the reflector/canopy assembly. The optical quality deployable membrane transmissive canopy (diameter = 10m) should achieve two years of use at about 100% transmissivity. Solar canopies (Mylar) have been demonstrated and ground tested (4x6m). Demonstrators exist for smaller scale articles.

Ideal transmission efficiency for two passes/photon through existing Mylar canopies is 81%. Actual efficiency is much less - about 63%. Transmission losses believed to occur due to high incidence angles of incoming and outgoing light. Ideal transmission through Mylar is believed possible through anti-reflective coatings. Solar testing techniques currently use a high-resolution CCD camera to photograph the Sun's image cast by the reflector. Current materials have not been scaled to required size or demonstrated in the relevant combined environments for the full mission life. Need to identify inflatable polymeric lightweight material(s) (conceptual reflector/canopy about 8.6% of total power antenna mass for Electric Propulsion systems), or combination of materials, capable of 100% optical transmission upon two passes/photon through the material over a period of at least 2 years.